Fractal Interrelationships in Field and Seismic Data

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Abstract

Size scaling interrelationships are evaluated in this study using a fractal model. Fractal models of several geologic variables are examined and include fracture patterns, reflection travel times, structural relief, drainage, topographic relief and active fault patterns.

The fractal properties of structural relief inferred from seismic data and structural cross sections provide a quantitative means to characterize and compare complex structural patterns. Studies were conducted using seismic data from the Granny Creek oil field in the Appalachian Plateau. Previous studies of the field reveal that subtle detached structures present on the limb of a larger structure are associated with enhanced production from the field. Vertical increases of fractal dimension across the zone of detachment provide a measure of the extent to which detachment has occurred. The increases of fractal dimension are greatest in the more productive areas of the field.

A result with equally important ramifications is that fracture systems do not appear to be intrinsically fractal as is often suggested in the literature. While examples of nearly identical patterns can be found at different scales supporting the idea of self-similarity, these examples are often taken from different areas and from different lithologies. Examination of fracture systems at different scales in the Valley and Ridge Province suggest that their distribution become increasingly sparse with scale reduction, and therefore are dissimilar or non-fractal. Box counting data in all cases failed to yield a fractal regime. The results obtained from this analysis bring into question the general applicability of reservoir simulations employing fractal models of fracture distribution. The same conclusions were obtained from the analysis of 1D fracture patterns such as those that might appear in a horizontal well.

Field studies of near-surface structure yielded results consistent with those obtained from the analysis of seismic data; structural relief exhibits fractal behavior. Along strike variations in the fractal dimension of structural cross sections were systematic and

provided a quantifiable measure of visible changes in mapped surface structure. Links between the fractal characteristics of structural relief to the patterns of accompanying fracture systems were not uncovered. Several variations in fracture pattern are encountered, however, the degree to which these variations are the result of scale change, has not been evaluated. The methods of fractal analysis can be applied to characterize fracture patterns, however, the presence of scale-variance requires that such analysis be carried out at a common scale.

Detailed investigations of surface topography in the Valley and Ridge area reveal a linear relationship between variations in the fractal dimensions of structural and topographic relief. Much of this interrelationship is undoubtedly related to structurally controlled variations in lithology across the surface. However, significant topographic changes occur across the Parsons CSD (cross-strike structural discontinuity) in areas where the large scale structure is invariant, and suggests that variations in the intensity of fracturing are the predominant erosional control in these areas.

The fractal characteristics of topography in the Plateau revealed little variance, and provided no hint as to the presence of faults forming the margin of the Rome Trough. This is not surprising since seismic data reveal that the deep structures of the Trough were largely inactive during deposition of the Pennsylvanian age sediments exposed at the surface across the area.

The dependence of topographic development on local structure was also investigated in an active tectonic area in central Japan. Analysis reveals a positive correlation between the fractal dimensions of active faults in the region and those of associated topographic relief. The fault zones are zones of weakness along which movement has occurred. Consequently, these zones are more easily weathered and eroded, contributing significantly to the topographic expression of the region. Exceptions to the relationship suggest that other factors may exert significant control on the development of topography in those regions, or that the active faults in those regions have not been detected or mapped. These relationships may be useful for earthquake hazard assessments.

The investigations conducted under this contract have carried fractal analysis from the stage of simple identification of fractal behavior to that of establishing interrelationships between the fractal characteristics of complex variables, and between fractal properties and geologic processes. Changes in the fractal characteristics of seismic reflection events, for example, allow one to quantify the relative abundance of detached structures. The fractal characteristics of surface topography can be used to predict those of near-surface structure. Future work is suggested by the results of work conducted under this contract. The ability to predict fracture behavior on the basis of larger scale structural interrelationships observable in seismic data or mapable in the field has not been solved. Further study incorporating stochastic and scale invariant descriptions of fracture patterns may reveal predictable relationships between the complexity of fracture networks and surrounding structure.

Approach

The various methods of fractal analysis employed in this study include roughness-length, compass-walk and box counting methods.

Roughness-Length

Malinverno (1990) defines a technique for use in the fractal analysis of self-affine profiles that is based on the earlier work of Brown (1987). A self-affine variable is defined by the following relationship (Turcotte 1989, 1992) $\sigma \propto \tau^H$ between the standard deviation (σ) and length of window (τ) over which σ is computed. H is referred to as the Hurst exponent (Mandelbrot 1983) and D = 2-H. The above relationship implies that the statistical properties of such series are invariant to rescaling of the dependent and independent variables. A variable is generally considered to be self-affine when the units of the dependent variable are different from those of the independent variable; for example, the spatial variation in gravity anomaly or neutron porosity variations versus depth. If the variable is a self-similar fractal, the variations over a small region of length or duration are equivalent to those of the whole profile when scaled by $1/\tau$. However, if the variable is a self-affine fractal, then rescaling of the dependent variable over the region of length τ by $1/\tau$ must be accompanied by rescaling of the dependent variable by the factor $1/\tau^H$ in order for variations over smaller intervals to exhibit the relative range of variation encountered over larger intervals.

Malinverno (1990) uses the above approach to describe profile “roughness” and refers to the standard deviation (σ above) as the root-mean-square roughness. Malinverno recommends detrending or removal of regional trends from the data. Significant regional trends were not present in the topography and seismic data analyzed in this study. The potential influence of trends in the data were assessed using model data. The results suggest that trend related errors in the estimate of fractal dimension are probably no more than 3% (Wilson et al. 1997). Errors associated with profile symmetry were also identified, and analysis of the data routinely excluded standard deviations of the largest data window. Profile symmetry led to invariance in between the largest and next-to-largest windows resulting in anomalously high *D* (see Wilson et al. 1997).

Compass walk

The compass dimension is derived from the relationship $N = Cr^{--D}$, where *N* represents the number of steps taken to traverse the profile, *r* is the step-length, and *D*, the fractal dimension. The relationship was proposed by Mandelbrot (1967) as a modification of Richardson’s (1961) observations.

Use of the preceding expression indicates that for fractal profiles, the perimeter length $P(= Nr) = Cr^{1-D}$. Non-fractal profiles have $D = 1$ and $P = C$ (i.e. the perimeter length remains constant regardless of the step size). However, even for non-fractal curves there is usually some increase in the perimeter length with decreases in the size of the compass-opening especially when the initial step-sizes are larger than the scale of the irregularities represented in the curve. Hence, in practice, lengths (*P*) or number of steps (*N*) measured using the larger compass opening are not included in the computation of *D*.

Box counting

The quantitative relationship obtained through box-counting is identical to that for the compass walk (i. e. $N = Cr^{-D}$). A profile, outline or area is covered by boxes of varying size, and the number of boxes required to cover the pattern is counted for each box size (e.g. Hirata 1989). For box counting, N represents the number of occupied boxes, and r is the length of the box sides. The box counting method is used in the analysis of fracture and active fault patterns.

Project Description

This research was conducted to examine the applicability of fractal characterization in the evaluation of numerous geologic variables such as deformed bed-lengths, reflection travel times, fold relief, drainage patterns, and fracture networks. Intrinsic to this study is a search for interrelationships between the fractal characteristics of different variables. Interrelationships between the size scaling properties of structural features observed in outcrop could serve as a guide in seismic evaluations of a reservoir and surrounding intervals. This research also brings into question the viability of the fractal model of fracture networks. Size scaling interrelationships combined with seismic and limited borehole data might provide insights into the nature of reservoir fracture networks early in the reservoir development stage.

The study is motivated by U. S. Department of Energy interest to accurately predict flow rates and flow patterns within fractured reservoirs. Accurate prediction requires an understanding of several reservoir properties including the geometry of the fracture network. The potential benefit of the proposed research is that it may provide a method for remotely assessing the size scaling properties of reservoir fracture networks and help guide field development.

Results

Seismic Evaluations

Seismic data evaluated in this study were taken from the Central Appalachian Plateau of West Virginia (Figure 1). The site consists of a relatively undeformed sequence of nearly flat lying sandstones, limestones, shales and coals associated with Pennsylvanian (Carboniferous) age distributary channel deposits (Figure 2). Seismic data across the study area (Figure 3) reveal the presence of normal faults extending out of acoustic basement several thousand meters beneath the surface. These faults define the east margin of an aulacogen known as the Rome Trough (Shumaker and Wilson 1996). Seismic data over the area reveal that the margin faults of this failed rift do not extend to the surface.

A set of six vibroseis lines were available over the area for analysis (Figure 2 and 4). The fractal dimensions of interpreted reflection events (Figure 5) were computed for all seismic lines. Average values of fractal dimension for these reflection events and their standard error (Figure 6) reveal the presence of systematic variation of fractal dimension from the basement to near-surface intervals.

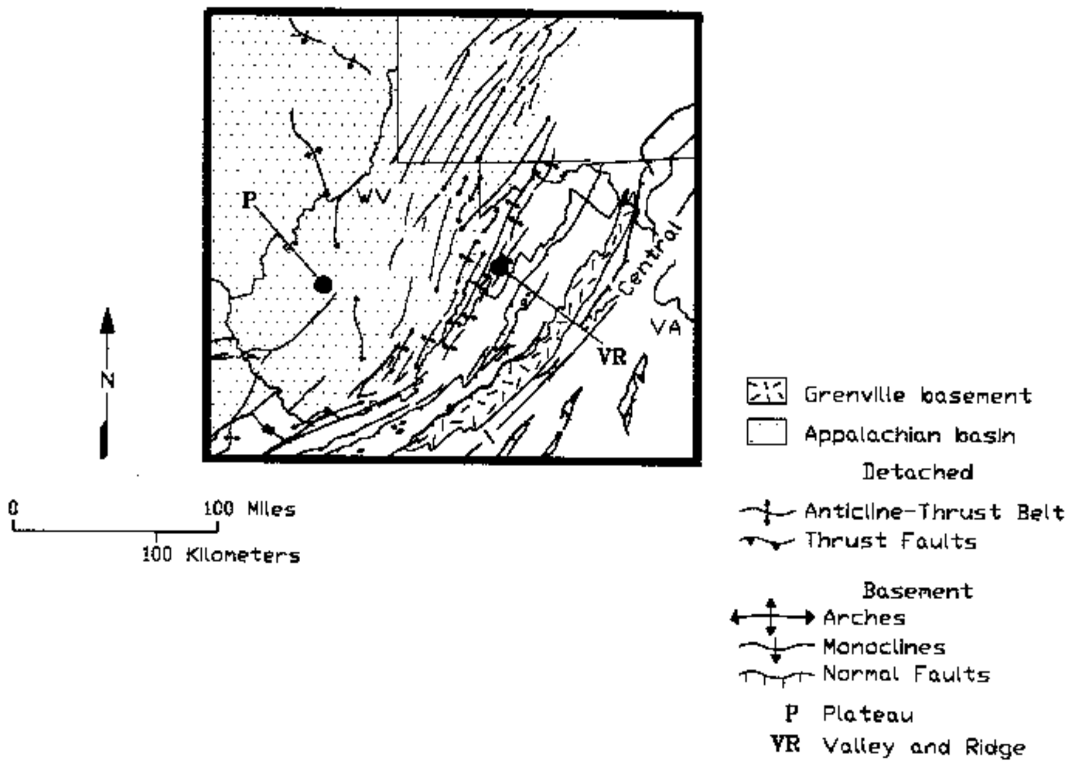

Figure 1: Locations of the Valley and Ridge (VR) and Plateau (P) areas of the central Appalachian mountains are shown.

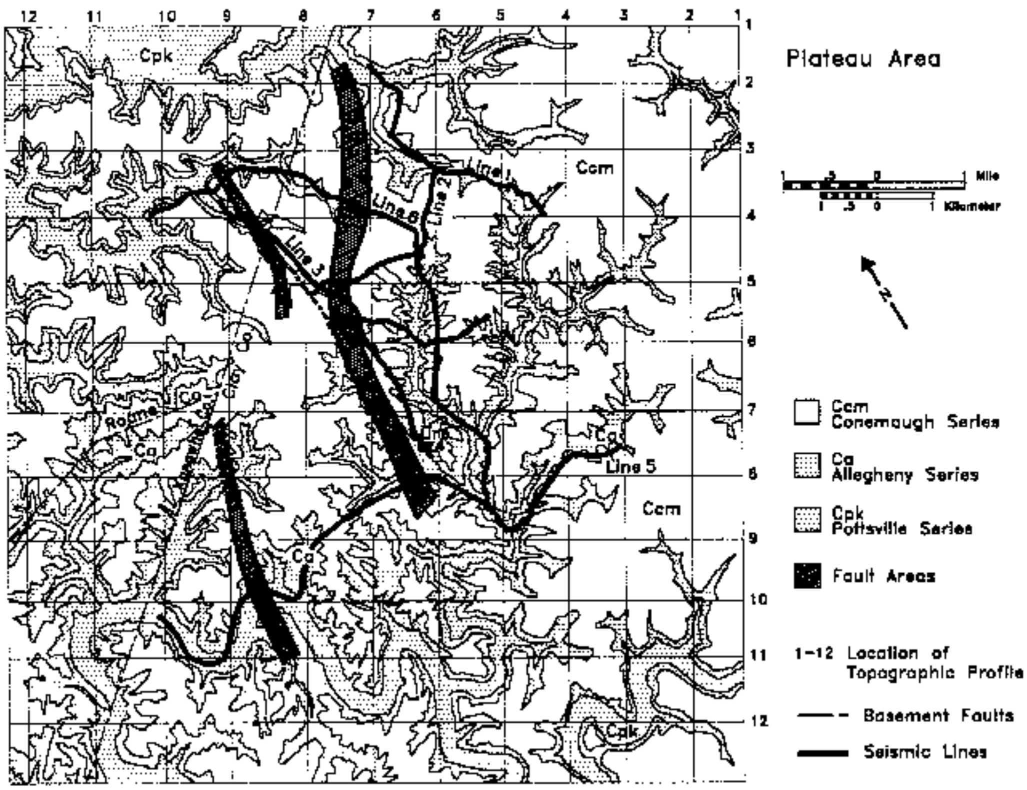

Figure 2: Geologic map of the Appalachian Plateau study area. NE-SW and NW-SE topographic profiles 1-12 are located along with seismic lines across the area and major basement faults.

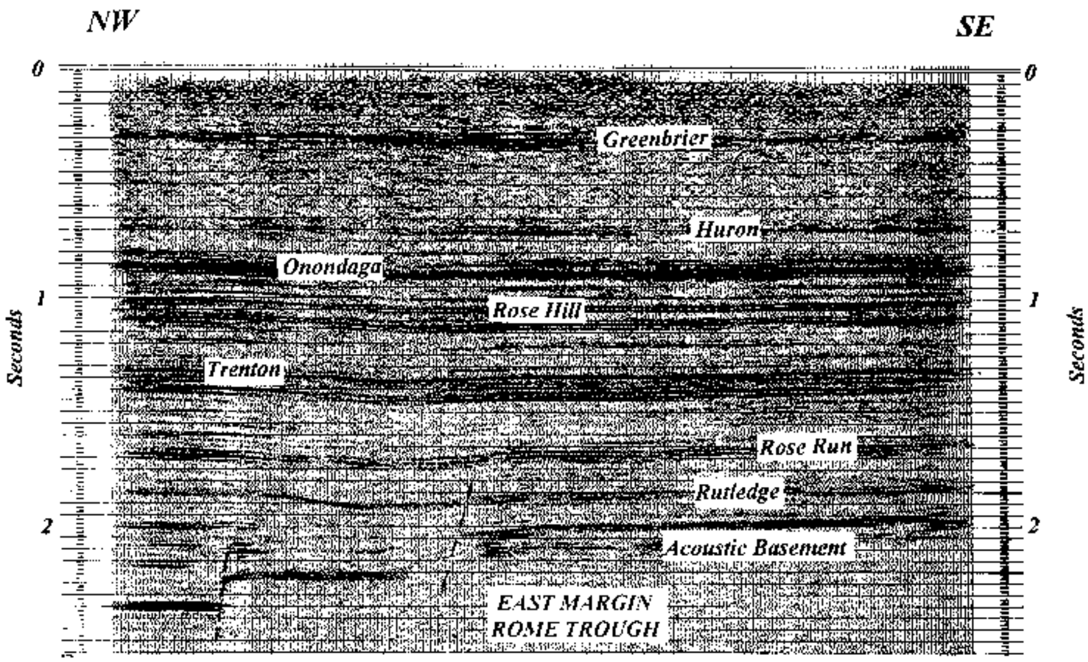

Figure 3: Seismic line across the Appalachian Plateau area (Line 6, Figure 2).

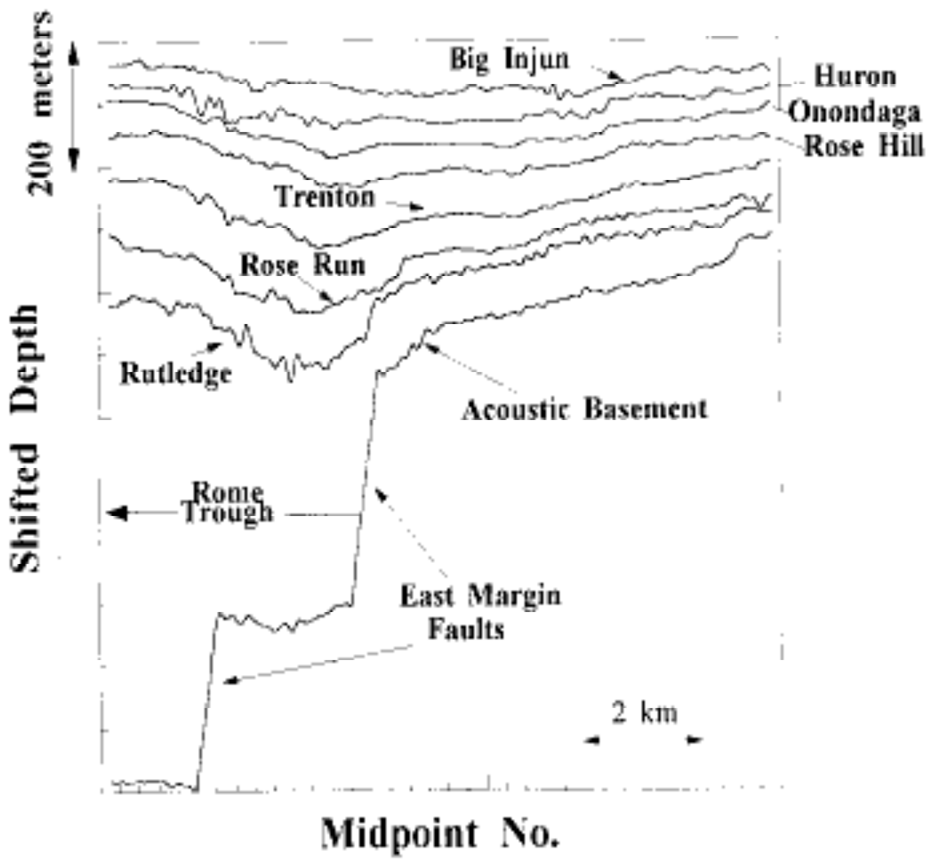

Figure 4: The reflection events labeled in Figure 3 have been converted to depth and then shifted relative to each other to enhance structural features across the margin of the Rome Trough.

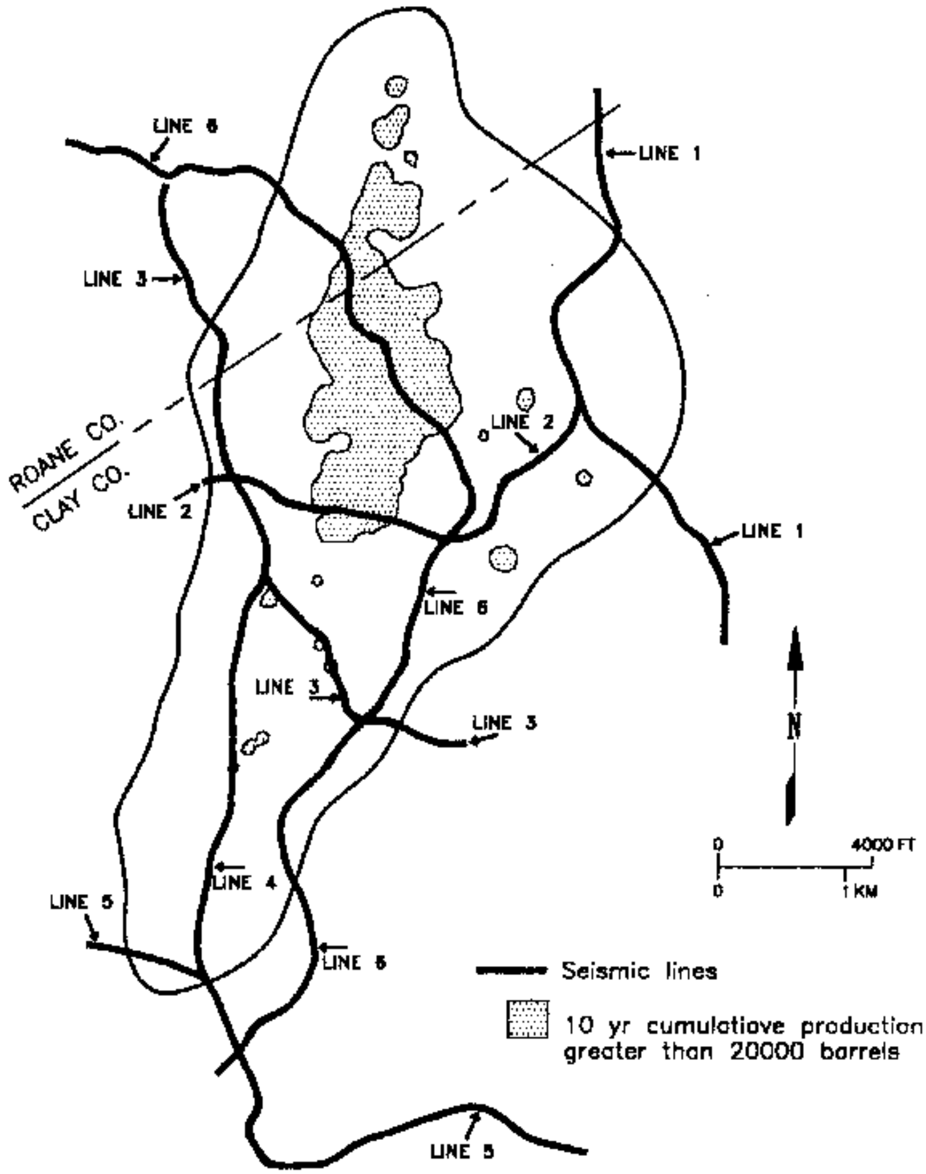

Figure 5: Locations of seismic lines over the Granny Creek oil field are shown relative to the highest producing areas in the field (areas with 10 yr. cumulative production greater than 20,000 barrels).

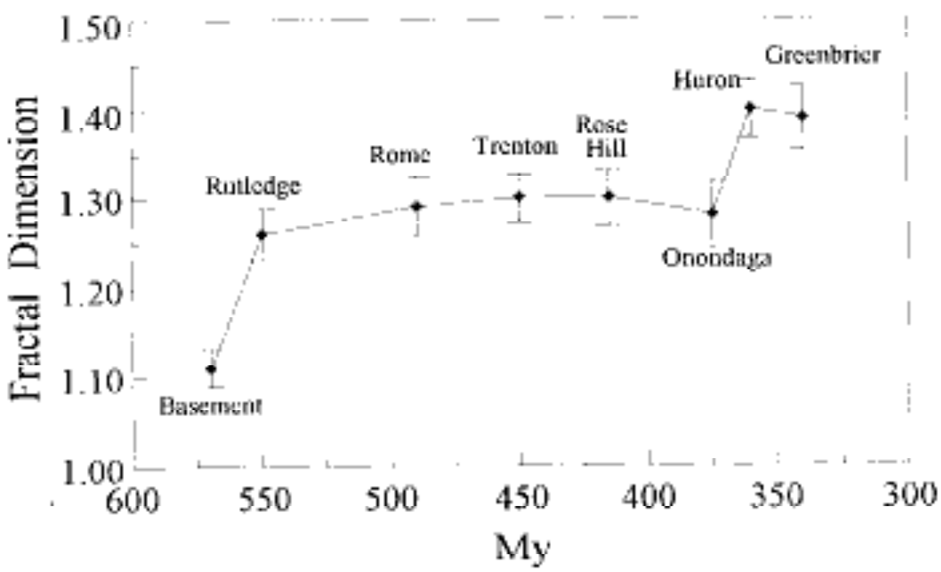

Figure 6: Fractal dimensions computed from reflection traveltimes of major reflection events observed on Line 6 are plotted versus reflector age.

The changes in fractal dimension quantify differences in reflector geometry. An abrupt increase in fractal dimension occurs between the basement and Rutledge reflection events. The basement and Rutledge events span the Middle and Late Cambrian period of geologic history. It was during this time that the main episode of failed rifting occurred (Shumaker and Wilson 1996). The relative proportion of different wavelength structures and their amplitudes do not change significantly from the Rutledge through Onondaga intervals. Subsurface intervals coinciding with the Rutledge through Onondaga reflection events extend from the Late Cambrian through Lower Devonian Periods. The fractal dimensions of reflectors in this interval are on average approximately 1.29. Another jump in fractal dimension occurs between the Lower Devonian Onondaga Limestone (D=1.28) and the Middle Devonian Huron Shale (D=1.4). Analysis of slickensides observed in cores from the Appalachian foreland (Evans 1980 and 1994) suggests that the Middle Devonian shales of the area are a decollement interval. Interpretation of the seismic data used in this study (Wilson et al. 1994, Hohn et al. 1994) reveal the presence of subtle detached structures above the Onondaga Limestone. Long wavelength structures in the overlying Huron and Greenbrier intervals have only slightly higher amplitude than the shorter wavelength structures, which leads to an additional increase in fractal dimension. The detached structures developed above Middle Devonian decollement zones combined with minor reactivation of the margin faults following deposition of these intervals yields lower relief structures and higher D for the overlying intervals. Detached structures are concentrated in areas just-west of the Trough-margin. The average fractal dimension of the shallow Greenbrier Limestone reflection event computed for portions of lines west of the margin (1.41) is slightly higher, but not statistically different from that for portions of the line east of the margin (1.36).

Line-to-line variations in fractal dimension (Figure 7) provide a quantitative measure of structural variability across the field. The extent to which detached structures are present in the area was assessed by computing the difference in fractal dimension between reflection events above and below the zone of detachment, i.e., the Huron and Onondaga reflection events, respectively, for each line. The results (Figure 7) reveal large differences in fractal dimension on lines 4 and 6 (Figure 4). These differences suggest that significant detachment related structural disharmony is present between these reflection events in the northern more productive areas of he field.

Fractal analysis quantifies the relative increases in reflector roughness, which indicates an increase in the intensity of detached structures. The intensity of detached structures is a production enhancing attribute of oil reservoirs (Wilson et al. 1994, Hohn et al. 1994) in this area and these quantitative evaluations serve as useful input to prospect ranking.

Fracture Analysis

Limited analysis of exposed fracture systems was undertaken in the Devonian Shales along two major structures in the Valley and Ridge province in the central Appalachians (Figure 8). Fracture patterns were photographed at several locations within the area (large dots Figure 8). Most of the sites are located in the Devonian shales which are confined to the northwest and southeast limbs of the Middle Mountain syncline. The organic rich shales exposed in this area are the equivalent of productive intervals buried beneath the Plateau which form significant fractured reservoirs of natural gas.

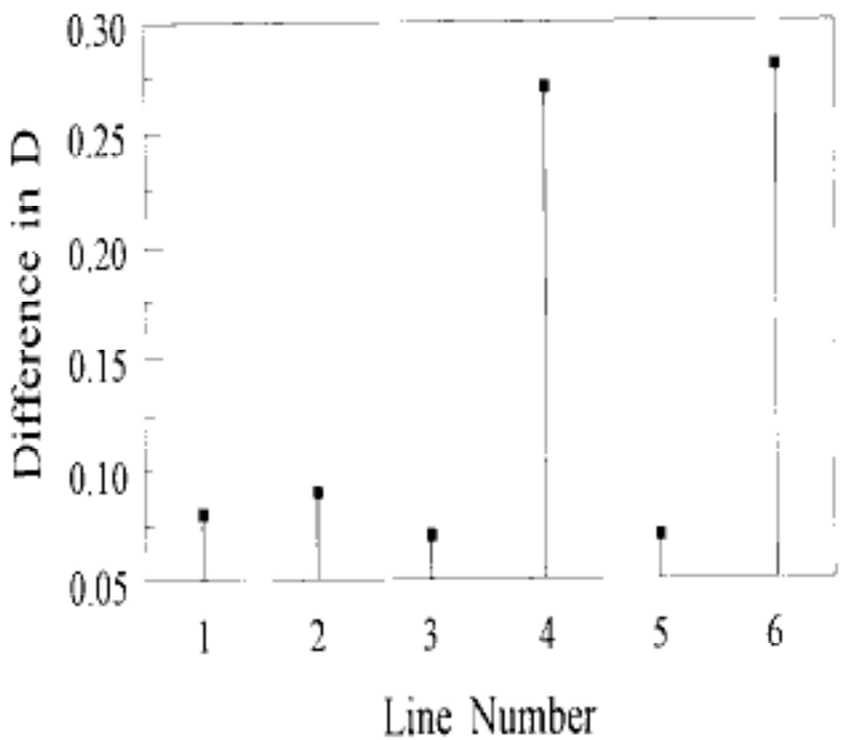

Figure 7: Difference in fractal dimension of the Huron and Onondaga reflection events, which lie above and below the zone of detachment respectively. The difference is shown for each seismic line.

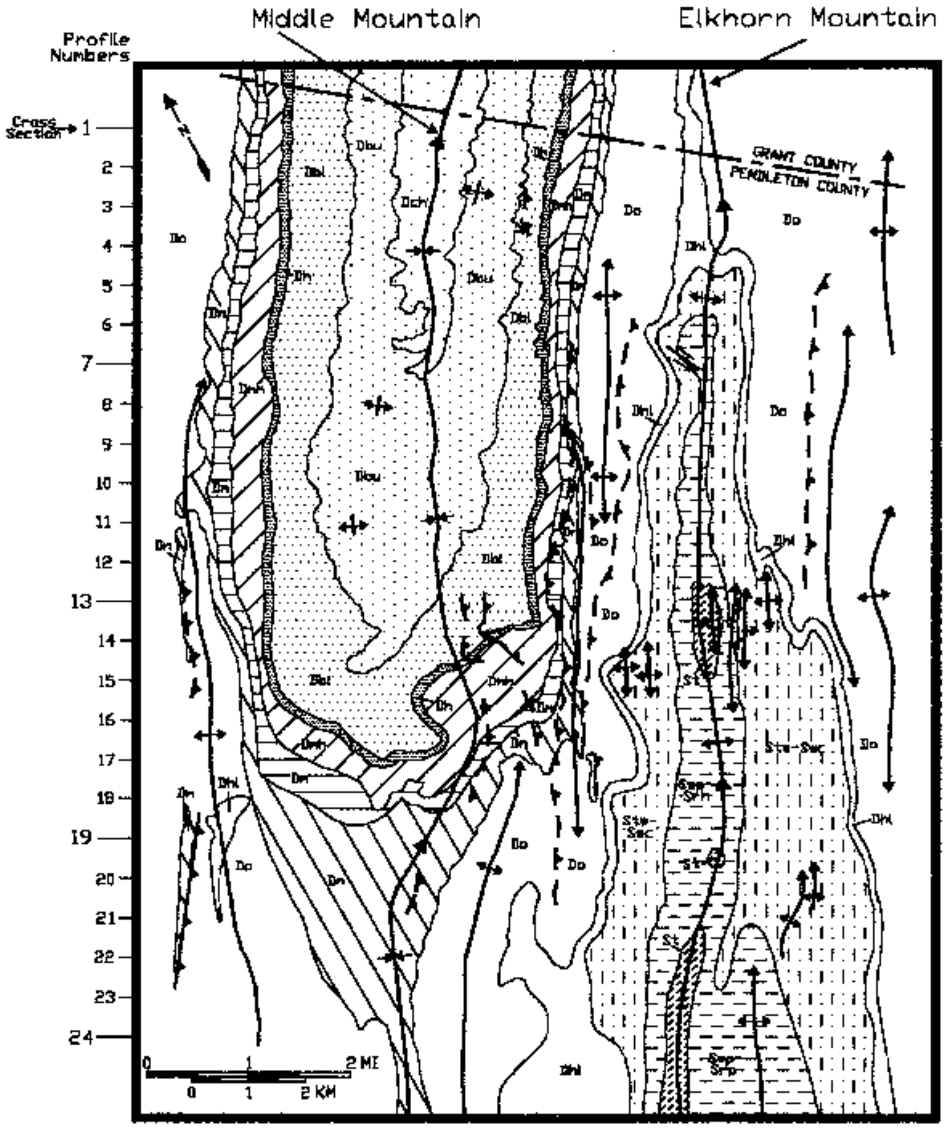

Figure 8: Detailed geologic map of the Valley and Ridge study area. Stratigraphic intervals exposed in the area extend from the Lower Silurian Tuscarora sandstone (St) to the Upper Devonian Chemung Formation (Dch). Locations of topographic profiles are noted along the left border of the map. Locations of structural cross sections are noted by the longer lines on the border. Station locations in the fracture studies are shown by large dots.

Systematic changes in the fractal dimension of structural and topographic relief were observed along strike of the major structures in the area. The extent to which fracture systems might be interrelated to local structure and exert control on topographic development was investigated using fractal analysis of fracture patterns. The results suggest that image scale rather than structural association may be the predominant factor controlling changes observed in the patterns formed by fracture systems.

This problem is illustrated using fracture patterns (Figure 9) observed in Devonian shale exposures on the northwest limb of Middle Mountain syncline (Figure 8). The maximum size (square) box used for the initial box-counting cover increases from 47 to 70 to 156 inches in Figures A, B, and C respectively. The fracture patterns reveal increasing levels of complexity that are due in part to the increased field of view. D varies from 1.36 to 1.26, and 1.43 for patterns A through C respectively (Figure 9). The log N vs. log r plots for these fracture pattern are typically non linear (i. e. non fractal).

In an attempt to eliminate scale-bias, fractal dimensions were recomputed for equivalent 45 by 45 inch subdivisions of each pattern. This yielded average fractal dimensions of 1.28, 1.23, and 1.1 for patterns A through C respectively, almost reversing the variations of D obtained from the entire field of view. However, this approach to the elimination of scale bias is problematical since the larger scale images do not resolve the same level of detail obtained in smaller scale images. For example, sketch C covers a 282 x 191 inch area so that features at the 40 x 40 inch scale are not represented as clearly or completely as those in photographs taken closer to the outcrop.

Another comparison (Figure 10) is taken from outcrops photographed along the southeast limb of the Middle Mountain syncline (Figure 8). The average fractal dimensions for patterns A through C are 1.42, 1.48, and 1.48 respectively. As in the preceding example, note that the scale range covered in pattern B extends over little more than half the range covered in A and C. It is likely that if an equivalent area were covered in the vicinity of B the fractal dimension would increase.

Recomputation of the fractal dimensions of 15 by 15inch subdivisions of the patterns in Figure 10 confirm this suspicion. Average fractal dimensions of 1.1, 1.41 and 1.43 were obtained for patterns A, B and C respectively. Individually they are less than values calculated for the entire pattern which again suggests that the patterns are not fractal since they vary with scale.

The failure of the fractal model as a representation of fracture networks requires that future analysis of interrelationships between variations in network patterns with variations in the intensity of associated folds and faults will need to be undertaken at the same scale.

Fractal Interrelationships

One of the primary objectives of this research was to investigate the use of fractal characterization as a means to quantify interrelationships between complicated variables. This investigation focused on interrelationships between the fractal characteristics of topography and structure. Fractal interrelationships between topography and structure are evaluated in two different tectonic settings: one in the intensely folded Central Appalachian Valley and Ridge province and a second along an incipient subduction zone in central Honshu Japan.This study has relevance to oil and gas exploration since, in

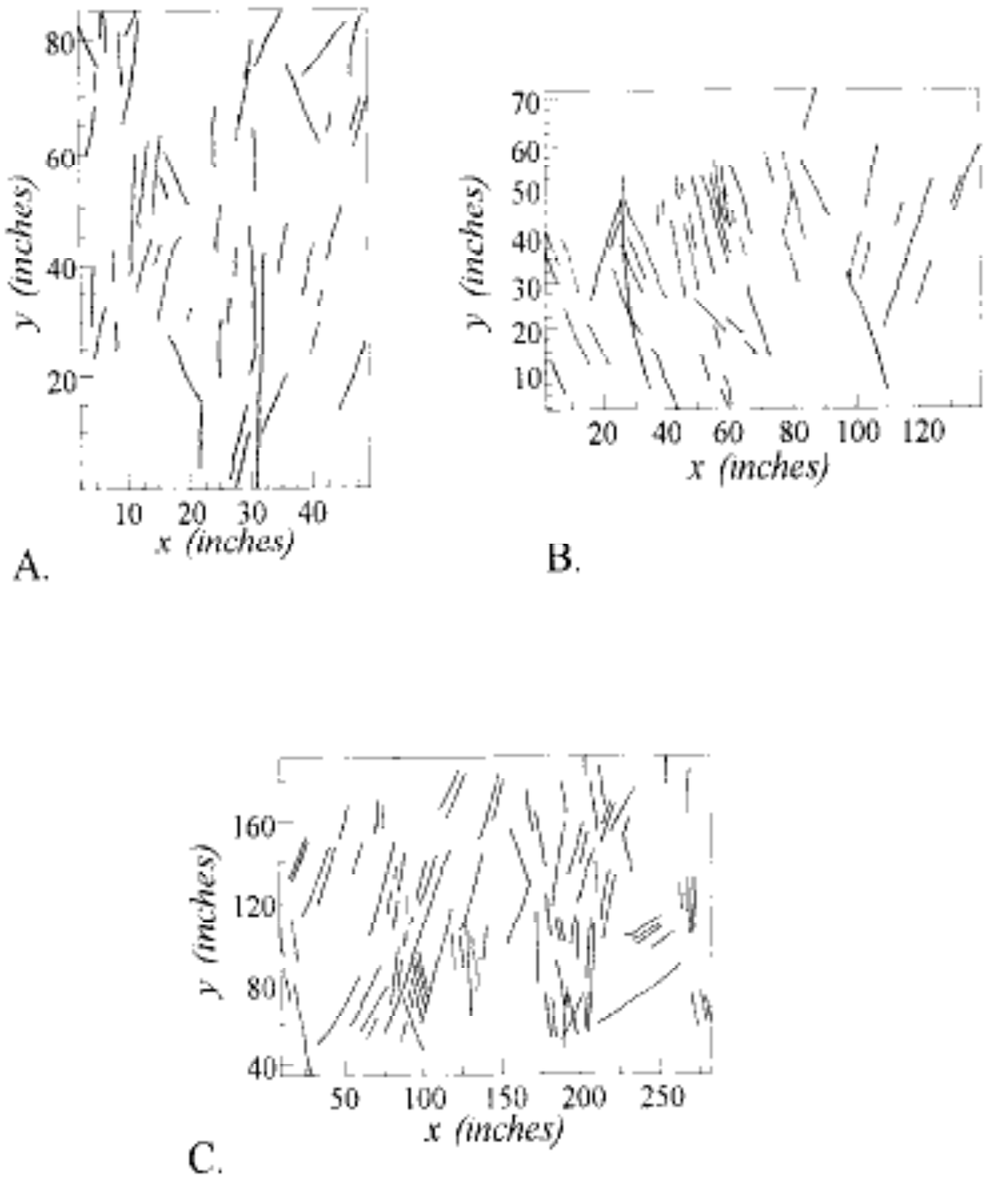

Figure 9: Fracture patterns observed at three different structural positions (northeast (A) to southwest (C)) along the *southeast* limb of the Middle Mountain syncline are presented.

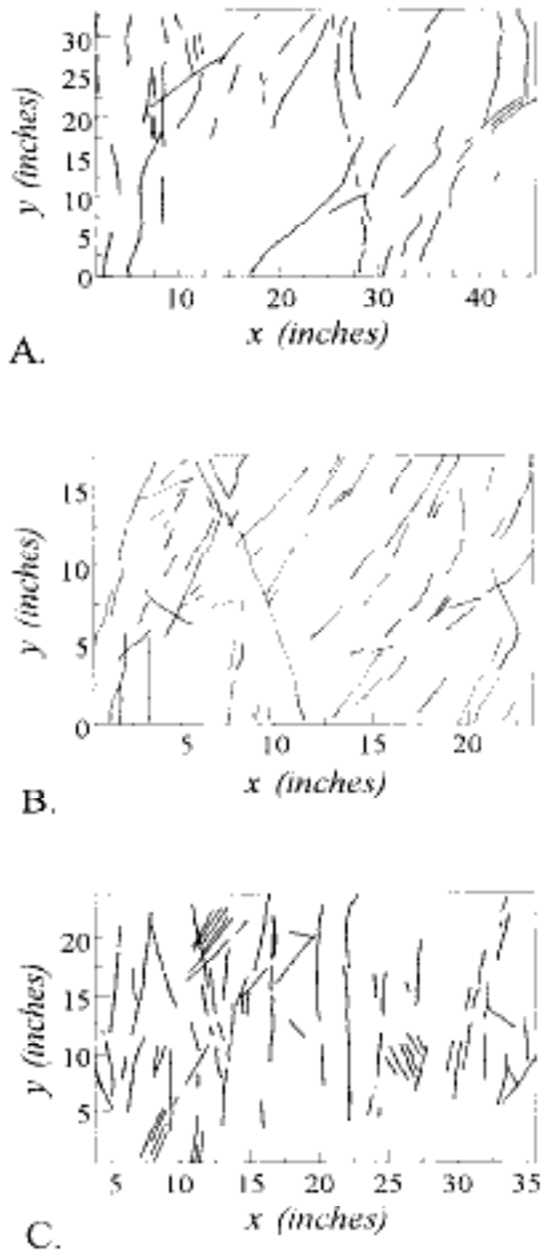

Figure 10: Fracture patterns observed at three different structural positions (northeast (A) to southwest (C)) along the *northwest* limb of the Middle Mountain syncline are presented.

the structural relief of the Oriskany Sandstone along 5 structural cross sections (Figure 11) . Regression analysis of this small population (Figure 12) yields correlation coefficients of 0.82 and 0.91(roughness-length and compass methods respectively) between the fractal dimensions of topography and structure. Although the size of the data set is limited, the results suggest a linear relationship between the fractal characteristics of topography and those of structure. Consider that this relationship may be more significant than it appears since geologic mapping of surface structure (Figure 8) reveals smooth structural transitions between profiles, thus construction and evaluation of additional geologic cross sections would yield intermediate values of fractal dimension and show similar correlation.

Topography in the northeastern part of the area is dominated by the Middle and Elkhorn mountains, which coincide with the Middle Mountain syncline and Elkhorn Mountain anticline. The linear relationship between the fractal dimensions of topography and structure quantifies the effect of deformation on the resistance to erosion of exposed rock formations. The fractal characteristics of topography provide a useful guide to locate and help quantify the extent of associated deformation intensity. The fractal characteristics of folds may also provide a useful tool for structural analysis since they estimate and allow one to incorporate the presence of small folds not represented on the regional scale cross sections (e. g. Wu 1993; Wilson 1997). The erosion of these ancient structures reveal their presence in surface landforms, and this relationship is describable by the interrelationship between their fractal dimensions.

Central Japan

The region selected for study in central Japan occupies a 270 by 220 km area that extends from 137^o to 139^o west longitude and from 35^o 20’ to 37^o 20’ north latitude (Figure 13). The area is divided by a major tectonic boundary known as the Itoigawa-Shizuoka Tectonic Line (ISL), which cuts through central Japan from the cities of Itoigawa on the north along the Japan Sea to Shizuoka to the south along the coast of the Suruga bay. In general the ISL is considered as the boundary between the westward pre-Tertiary rocks of southwest Japan and the eastward Tertiary rocks of northeast Japan (Kato 1992). The ISL is also believed to lie along a zone of incipient subduction between the North American and Eurasian plates (e.g. Nakamura 1983, Kobayashi 1983). Active faults within the study area (Figure 14) were compiled from the revised editions of active fault maps (Research Group for Active Faults of Japan 1991). The abrupt decrease in fault intensity observed from southwest to northeast occurs across the ISL.

Studies of the fractal characteristics of active-faults in Japan are presented by Hirata (1989) and by Matsumoto et al. (1992). Hirata’s analysis covered most of Japan, and was conducted on 1^o longitude by 40’ latitude areas roughly 90 by 74 km in size using active-fault sheet maps of Japan published by the Research Group for Active Faults of Japan (1980). Matsumoto et al. (1992) analyzed relatively narrower strip-like regions along the Median Tectonic line and the Izu Peninsula using data from the Research Group for Active Faults of Japan (1980) and also the Research Group for Active Tectonic Structures in Kyushu (1989). Hirata (1989) and Matsumoto et al. (1992) employ different methods to estimate the fractal dimensions of active fault distribution. Hirata uses box counting (e.g. Turcotte 1989, 1992), while Matsumoto et al. (1992) use the method of Okubo and Aki (1987) which is based on counts of the number of circles of varying radius needed to cover the fault traces.

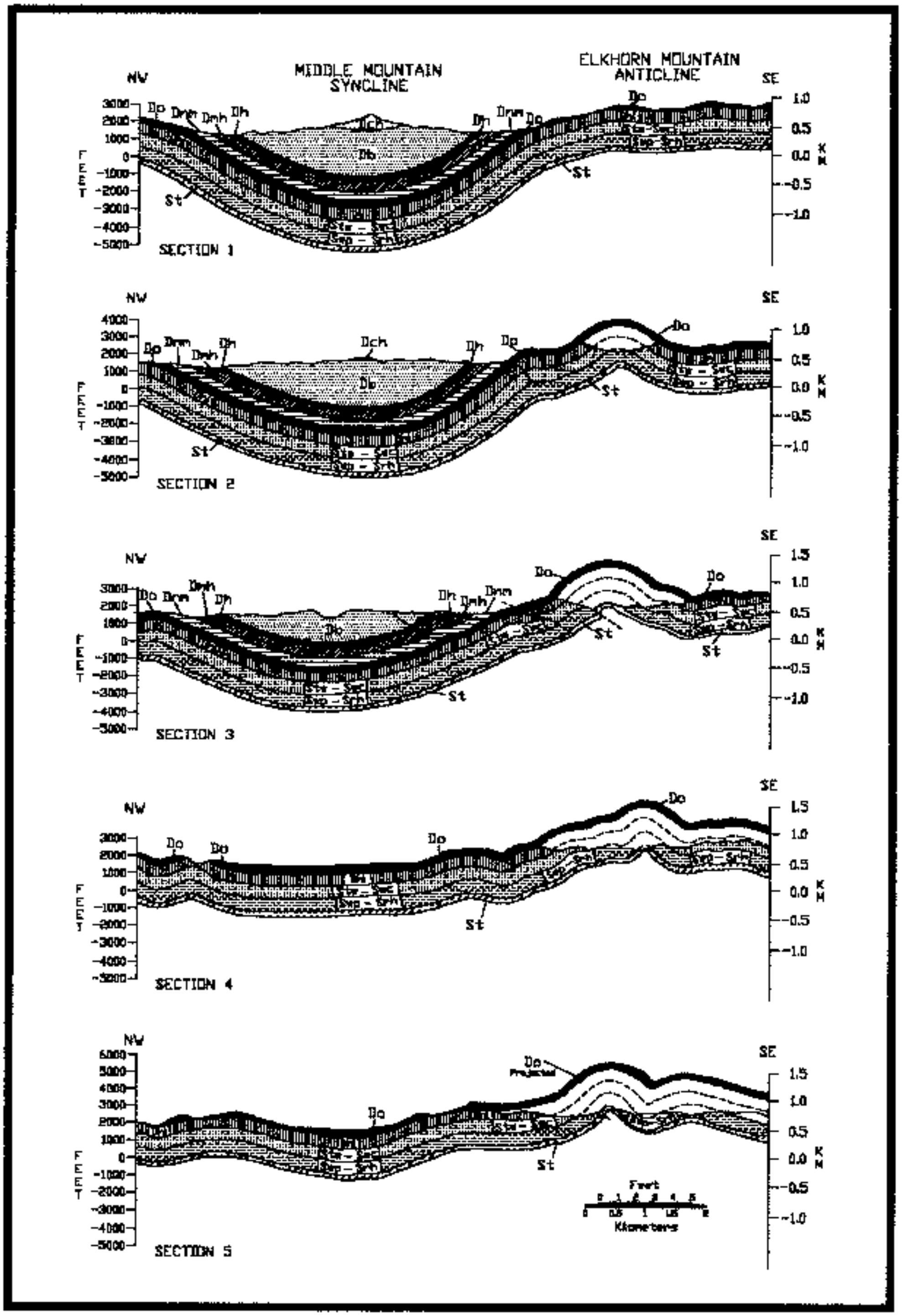

Figure 11: Structural cross sections constructed northeast-to-southwest through the area lie along topographic profiles 1, 7, 13, 19 and 24 (see Figure 8).

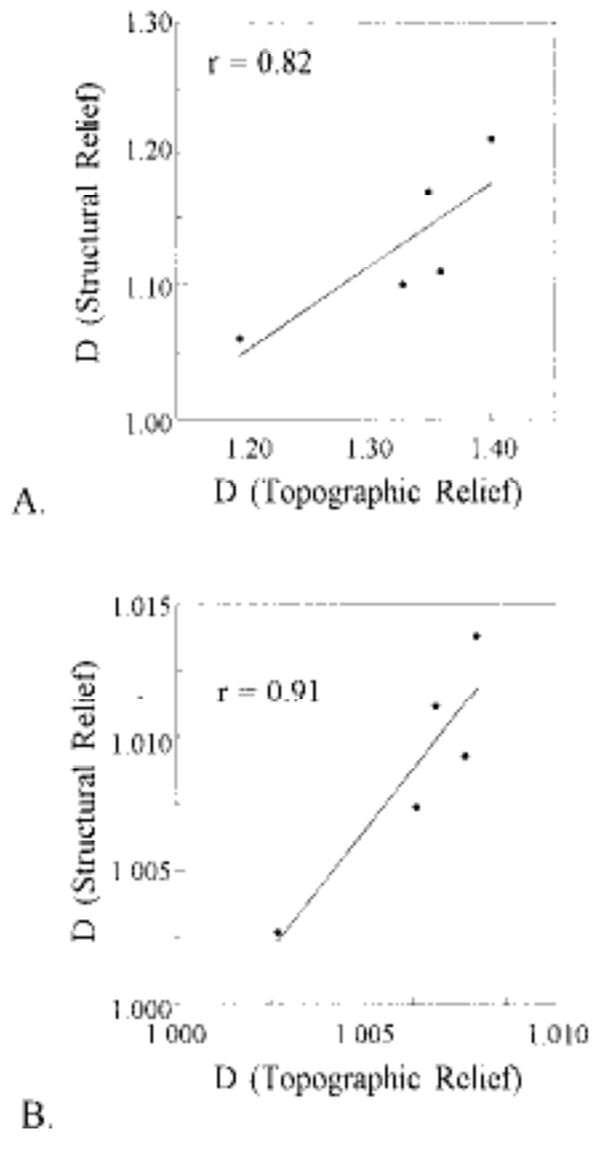

Figure 12: Fractal dimensions of topographic and structural relief are crossplotted for both (A) roughness-length and (B) compass estimation methods.

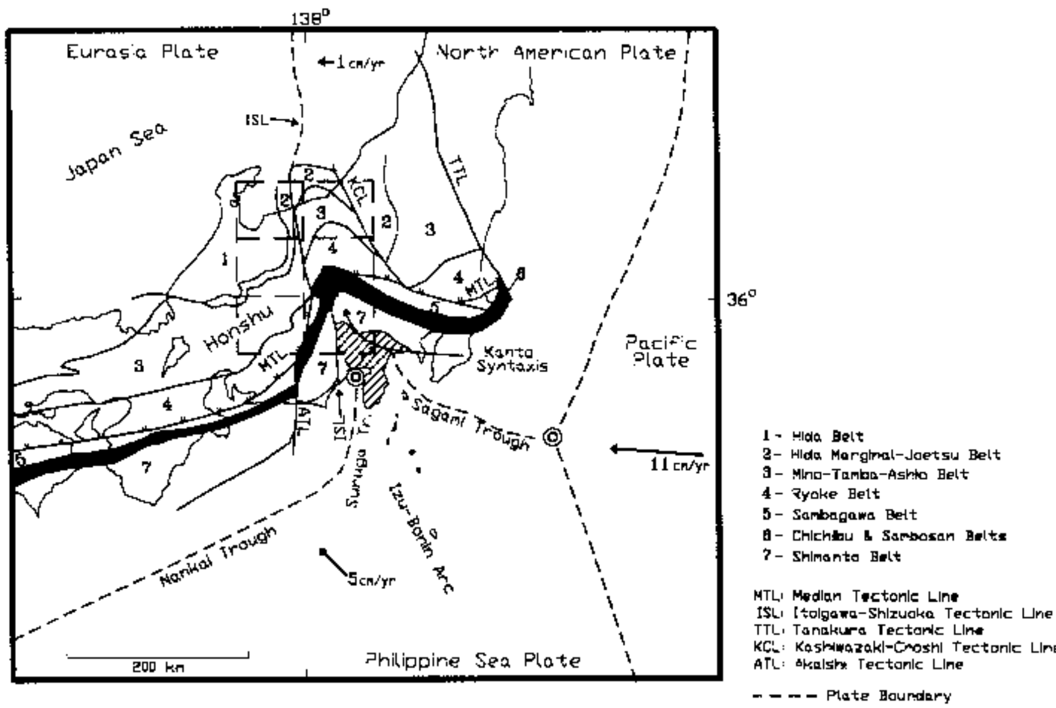

Figure 13: Tectonic map of central Japan shows the location of the study area and its subdivisions (heavy dashed lines). Major tectonic boundaries are noted. Taken from Niitsuma (1989).

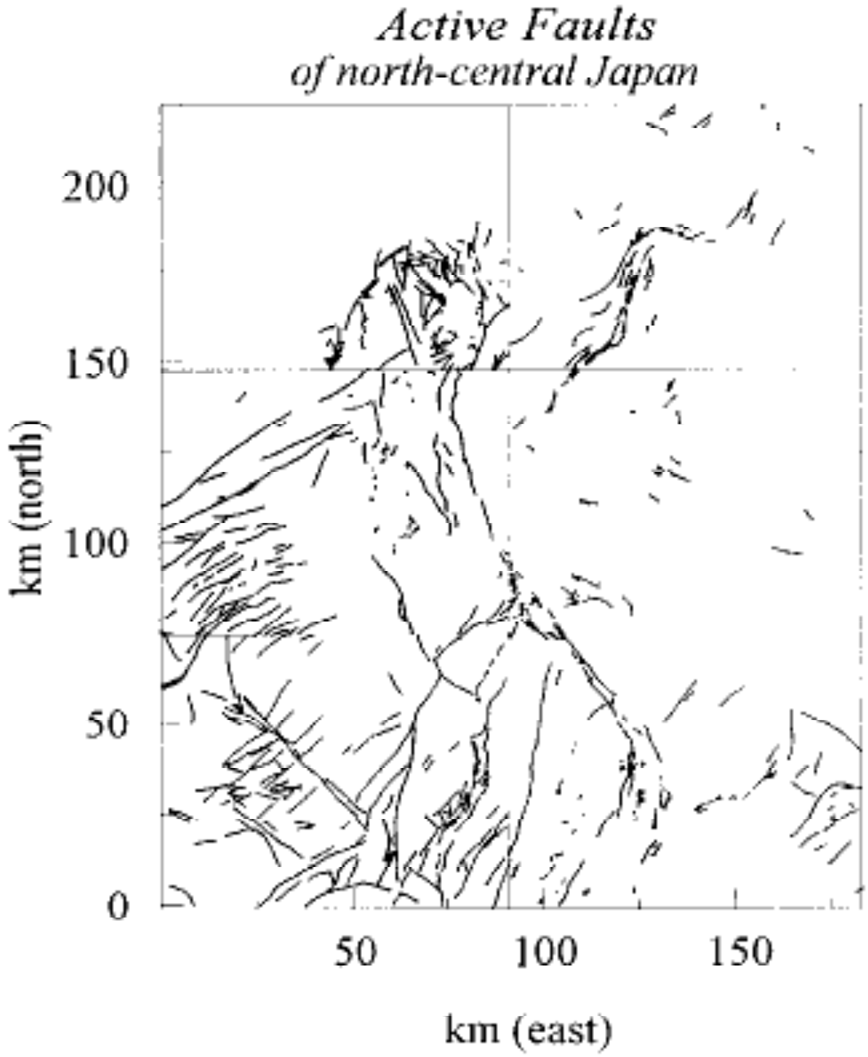

Figure 14: Active faults mapped in the central Japan study area. Subdivisions of the study area are shown. The rectangular grid divides the study area into 1^{o} (longitude) by 40’ (latitude) subdivisions corresponding to individual 1:200,000 scale active fault maps of the area.

The results of Matsumoto et al. and Hirata are not directly comparable, but, in general, they support a fractal model of fault distribution with a few exceptions. Matsumoto et al. (1992), for example, present the boxplot for an area along the Median Tectonic Line that is characterized by two linear regions in the log-log plots. Hirata notes that in several areas a fractal distribution was not observed and excludes those regions from his analysis. Hirata's analysis of box-count data is restricted approximately to the 2-20 km range of scales, while the results of Matsumoto et al. (1992) appear to be restricted to the 1-10km range of scales. Based on outcrop scale studies of fracture patterns in the North Izu Peninsula area, Hirata (1989) suggests that the fractal characteristics of fractures on the 10^{-1} to 10^{-2} meter scale are similar to the larger scale active fault patterns. Hirata's results also indicate that the fractal dimensions of active fault systems are highest in central Japan and decrease from southwest to northeast Japan. The following analysis is concentrated across this area of transition in central Japan.

Updated active fault maps were obtained for the study area from the Geological Survey of Japan. Box counting was used to determine the fractal dimensions of active faults in the area. As noted in the preceding section on fracture analysis, point-to-point slopes over the interval used to compute the best fit line varies gradually from higher slopes for the largest boxes to smaller slopes for the smaller box sizes. In this study, analysis was conducted over the approximate 3-19km range. The correlation coefficient for the slope of the regression line fit to the data in this region is always greater than 0.99.

Active fault/Topography Correlation: Fractal dimensions for the active fault patterns were computed for two 70 by 70km regions in each 1^{o} longitude by 40' latitude sheet. There was 50km of overlap between areas in the east-west direction. Analysis of the fractal characteristics of topography were made using 1^{o} longitude by 40' latitude topographic sheets that cover the areas shown in Figures 13 and 14). Nine east-west profiles were constructed at intervals of 5 minutes latitude for each topographic sheet. Topography was digitized at 0.5 km intervals and a roughness-length computation of fractal dimension was made for each profile. The average D for 70km long subdivisions of the nine profiles lying within the area used to box count the active faults was taken as the representative fractal dimension for the topography in that area.

A plot of the fractal dimensions of topography versus those of the active faults (Figure 15) has a positive slope of 0.16 and intercept of 1.2. The correlation coefficient of the regression line is 0.7. The data point associated with the western 70km subdivision of the Kofu region is a notable exception to this linear trend. The fractal dimension of topography in the Kofu region is anomalously high. Structure in the Kofu region is quite complex. The area includes major tectonic boundaries (e.g. the Median Tectonic Line (MTL) and ISL) and lies almost entirely within an area known as the Kanto Syntaxis (Figure 13). The Kanto Syntaxis is represented by a cusp-shaped bend in the pre-Miocene terranes. From southwest to northeast across the Akaishi Tectonic Line pre-Neogene formations undergo left-lateral slip of nearly 60km (e.g. Matsuda 1978). ENE-WSW trending pre-Neogene formations exposed along the Median Tectonic Line in southwest Japan (MTL) are rotated into a nearly NS trend, and farther to the east across the ISL, they are rotated even farther into a NW-SE trend (Kato 1992). The large structural bend

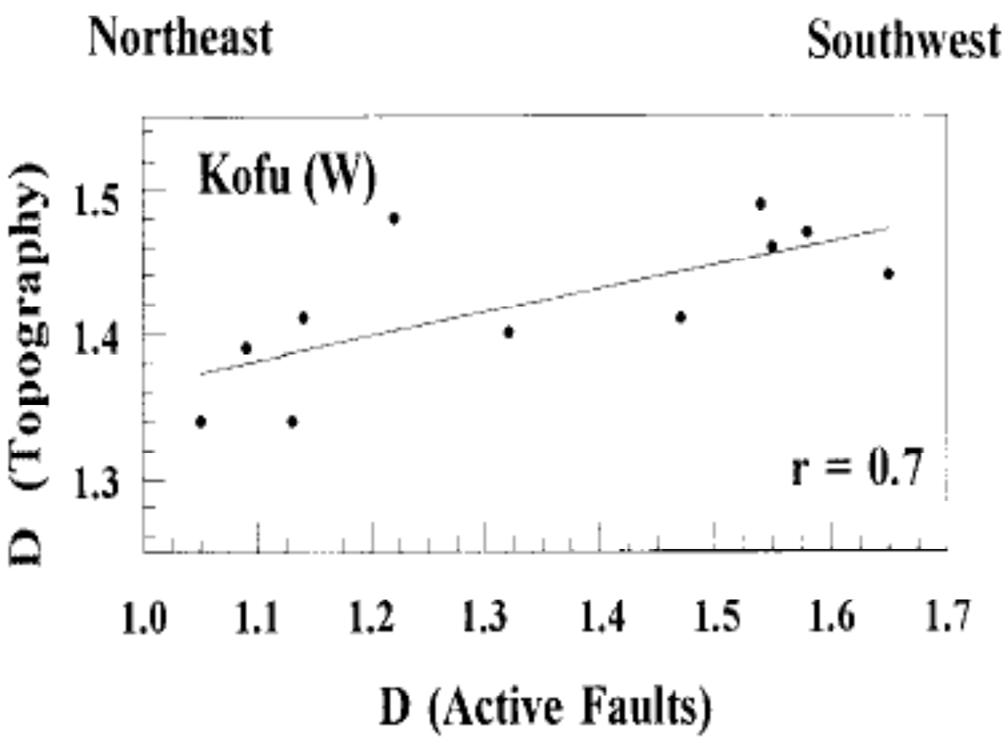

Figure 15: Linear regression line fit to the fractal dimensions of topography versus those of active faults yields a correlation coefficient of 0.7.

occurring through the Kanto Syntaxis (Figure 13) is the result of active collision of the Izu Bonin arc into central Japan beginning in the Late Miocene (Takahashi and Nomura 1989, Niitsuma 1989). The result and structural complexity of the Kofu area suggests that the distribution of active faults may be underestimated. Based on the linear relationship between D_{Top} and D_{AF} the distribution of active faults in the Kofu area may actually be more like that observed in the Iida area. Distributions of isolated faults may be connected and numerous faults may be hidden by recent sedimentation in the Kofu region. Elimination of this point from computation of the regression line increases the correlation coefficient to 0.84.

Benefits

Fractal analysis of seismic reflection events provides a quantitative description and differentiation of structural variability occurring along and between reflection events. Fractal analysis was able to detect both subtle and major differences in structural variability identified in prior interpretation of the data (Wilson et al. 1994; Hohn et al. 1994). As such, fractal analysis of seismic reflection data provide a means to compare and contrast differences in reflector geometry not only within a single area, but between different areas. Fractal analysis has rank-assessment potential, illustrated in this study by its ability to identify areas where detached structures are most predominant.

The fractal model is often assumed in describing the complex patterns formed by fracture networks (e.g. Barton and Hseih 1989; Barton 1995), however, the viability of the fractal model has not been clearly demonstrated in a single area at multiple scales. The studies conducted in this study (Wilson et al. 1997) suggest that the fractal model is not universally valid. Pattern complexity is observed to decrease with scale. These changes in pattern complexity appear to be curvilinear rather than multi-fractal. Evaluation of scaling interrelationships between structure and fracture networks will require standardization of observation scale. The accurate representation of fracture systems is necessary in the accurate simulation of production history (e. g. McKoy and Sams, 1996). Further research is needed to yield more accurate conceptual and quantitative models of complex fracture systems that can be incorporated into production history simulations of fractured reservoirs.

This study indicates that fractal interrelationships exist between topography and near-surface structural relief. The fractal characteristics of near-surface structure, whether active or inactive, are related linearly to topography through their fractal dimension. In areas where near-surface structure is absent (e. g. the Appalachian Plateau area) the fractal characteristics of the topography are invariant (see Wilson et al. 1997).

Exceptions to relationships between active faulting and topography may have significance within the context of the long term earthquake activity within the area. Fractal analysis may provide a means to assess the relative frequency of earthquake activity over time periods that extend beyond the historical record. The relatively high fractal dimension of topography in the Kofu area may imply that long term earthquake activity is more intense than suspected based on current frequency of occurrence and active fault distribution. Comparison of the fractal characteristics of topography and active structures may offer a possible tool to compliment regional earthquake hazard assessment.

Future Activities

A fractal model is often assumed in describing the complex patterns formed by fracture networks (e.g. Barton and Hseih 1989; Barton 1995), however, the viability of the fractal model has not been clearly demonstrated in a single area at multiple scales. Studies conducted under this D. O. E. contract (Wilson et al. 1997) suggest that the fractal model is not universally valid. Pattern complexity is observed to decrease with scale. These changes in pattern complexity appear to be curvilinear rather than multi-fractal. The accurate representation of fracture systems is necessary in the accurate simulation of production history (McKoy and Sams, 1996). Future research is needed to yield more accurate conceptual and quantitative models of complex fracture systems that can be incorporated into production history simulations of fractured reservoirs.

The potential for developing empirical relationships between topographic relief, active faulting, and seismicity offers some possibility of providing information helpful to seismic hazard assessment. Continuation of the above study is being pursued to undertake fractal analysis of the spatial distribution of seismicity along with interrelationships to other parameters such as earthquake magnitude, seismic moment, and cumulative energy release. This research may provide basic information related to earthquake hazard assessment in active tectonic areas.

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